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# Sensitivity of NOGAPS Forecasts to UAS-like Observations

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**14. ABSTRACT**

An adjoint-based method is used to calculate the impact of in situ upper-air observations from a data-austere region of high meteorological variability (Almaty, Kazakhstan) on short-range forecast error in the Navy Operational Global Atmospheric Prediction System (NOGAPS). During the May 2006 – July 2007 study period, Almaty Aircraft Meteorological Data Relay (AMDAR) ascent and radiosonde observations assimilated at 00 UTC have large beneficial impacts on forecast error reduction when compared to average global AMDAR ascent and radiosonde observation impacts. For Almaty, the average impact of an AMDAR ascent observation is more than twice as beneficial as that of a radiosonde observation in the reduction of forecast error in the global domain. The large beneficial impact of Almaty AMDAR ascent observations offers great promise for the beneficial utilization of weather data from unmanned aircraft systems (UAS) deployed in similar environments. Currently, the long-endurance medium-altitude Predator flown by the USAF and others is the most suitable UAS platform available for AMDAR-like surface to mid troposphere atmospheric profiling. The acquisition of both test and in-theater Predator data and the concurrent examination of how such data impacts the accuracy of short-range forecasts in data-sparse regions are ongoing at NRL.

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# SENSITIVITY OF NOGAPS FORECASTS TO UAS LIKE OBSERVATIONS

## 1. Introduction

Developed at the Naval Research Laboratory-Monterey, the Navy Atmospheric Variational Data Assimilation System (NAVDAS) is used for the analysis cycle of the global forecast model, the Navy Operational Global Atmospheric Prediction System (NOGAPS). Observations are routinely assimilated from platforms that include satellites, aircraft, radiosondes, land surface stations, ships and buoys. On a limited scale, dropsonde observations and synthetic wind and sea level pressure data are also utilized. The impact of different observation types on NOGAPS short-range forecast error in the global domain has been documented (Langland, 2005). One significant result of that study was the large beneficial impact on forecast error from commercial aircraft data. Further evaluations of observation impact on NOGAPS forecast capability are ongoing at NRL, with more than a year of study data available.

Over the last decade, the use of unmanned aircraft systems (UAS) has become increasingly common for a variety of military and commercial applications. A UAS has great potential as a weather observing platform. As an auxiliary to routine UAS operations, on-board weather sensors can provide in-situ observations in data-sparse regions where such information is critical for improving weather forecasting. Depending on its size and flight characteristics, a UAS could provide high altitude or low level weather data, profiles of the atmosphere (similar to a radiosonde) during flight ascents and descents or long duration meteorological data at a constant level.

The utility of atmospheric observations from tactical unmanned aeronautical vehicles has been tested (Pauley et. al., 2005). In this preliminary evaluation, weather data from Predator UAS flights out of Creech AFB, Nevada, were transmitted to a ground control station, encoded as aircraft weather observations using the World Meteorological Organization (WMO) Aircraft Meteorological Data Relay (AMDAR) FM-42 format, then placed into a conventional observation file used by NAVDAS. Subsequent comparisons to NOGAPS background fields as well as available radiosonde and commercial aircraft ascent/descent data near the flight test area demonstrated the feasibility of using UAS data in numerical weather prediction.

Due to ongoing data transfer permission and logistic issues, tactical UAS observations have yet to be included as a regular data type assimilated into operational Navy weather forecast systems. In the meantime, it is instructive to use existing commercial aircraft data as pseudo UAS observations to examine the degree of impact such data from a data-austere region can provide on the reduction of model forecast error. Specifically, in this report, NRL’s observation sensitivity capability is used to document the observation impact of routine Lufthansa flights into Almaty, Kazakhstan, as pseudo UAS observations.

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## 2. Observation Impact Methodology

The adjoint-based diagnostic technique for calculating the impact of observations on short-range forecast error is fully described by Langland and Baker (2004). Their observation impact calculation uses adjoint versions of NOGAPS and NAVDAS to estimate the difference between quadratic measures of forecast error as a sum of individual observation impacts. Although this method evaluates all observations simultaneously, it conveniently permits any individual observation (or selected subset of observations) to be quantified as a separate value.

A NAVDAS analysis $x_a$ is produced by assimilating observations and correcting a background $x_b$, which is a forecast started six hours earlier. The forecasts started from $x_a$ and $x_b$ follow trajectories f and g, respectively, and evolve to $x_f$ and $x_g$ at time t. Scalar forecast error $e_f$ and $e_g$ are defined as energy norms (in units of specific energy J/kg). Generally, $x_a$ will be a better approximation of the true atmospheric state than $x_b$, and so the short-range forecast error $e_f$ on trajectory f will be less than the forecast error $e_g$ on trajectory g.

In this study, the f trajectories are 24 hr forecasts starting at 00 UTC and the g trajectories are 30 hr forecasts starting from 18 UTC. Both sets of forecasts verify at 00 UTC. The forecast error $e_{24}$ and $e_{30}$ are defined in the global domain between the surface and a level near 150 hPa. The NOGAPS configuration includes 30 vertical levels at approximately 1.5° horizontal resolution. The version of NAVDAS is identical to that used for operational data assimilation at Fleet Numerical Meteorology and Oceanography Center (FNMOC).

For short-range forecasts, an estimate of the actual forecast error difference $e_f - e_g$, defined as a scalar quantity $\delta e^g_f$ and referred to as the "observation impact," can be calculated using innovations (observation – background values) and adjoint-derived sensitivity gradients. These calculations provide more than first-order accuracy in the estimate of $\delta e^g_f$, because sensitivity gradients on both the analysis and background trajectories are used. However, the accuracy of $\delta e^g_f$ is limited somewhat by tangent linear approximations used in the forecast model adjoint.

As computed, negative $\delta e^g_f$ impact values are "beneficial", since they imply error reduction. In order to compare the relative value of different sets of observation types, the " impact per observation" is obtained as the cumulative impact for a given set of observations divided by the number of observations in that set of data. Because data assimilation uses statistical assumptions that apply in the mean sense, data types comprised of large number of observations will inevitably reduce forecast error in terms of cumulative impact. However, in any individual forecast, there are large numbers of observations (perhaps even small data sets) which do not reduce forecast error. Such nonbeneficial observation impacts ($\delta e^g_f > 0$) could result from a data quality or observation instrument problem. Also, due to an inherent dependence on other data in the assimilation process, any individual observation might prove nonbeneficial if the specified observation or background errors used to assimilate the datum were not accurate. Finally, if the observation types in a dynamically sensitive region are relatively few in number, the potential of an individual observation to have a larger impact on the forecast outcome is increased.

## 3. Observation Impact Results

Almaty (formerly named Alma-Ata during the Soviet Union era) is the principal city of the expansive central Asian nation of Kazakhstan. Its climate is continental, marked by cold winters and hot summers and moderate precipitation, heaviest in the spring. For meteorological data assimilation purposes, the only sources of in-situ upper-air data at Almaty and its surrounding area out several hundred kilometers are scheduled twice daily airport radiosondes (WMO station 36870, 43.2° N, 76.9° E, elevation 847 m) and aircraft AMDAR reports. As such, Almaty is an excellent site to examine the impact of spatially limited observational data on short-range forecast error. For this study, AMDAR ascent reports (primarily from Lufthansa flight LH647 which departs Almaty at 03 hour local, or 22 UTC) are available within the NAVDAS 00 UTC assimilation cycle. These AMDAR ascents are examined in conjunction with Almaty 00 UTC radiosonde soundings, then compared with similar data computed in the complete global domain.

Observation impacts (cumulative, per observation, per profile) and related data counts from AMDAR ascent and radiosonde observations assimilated into NAVDAS at 00 UTC during the study period May 2006 – July 2007 are given in Table 1 both globally and for Almaty alone. For AMDAR ascent observations (temperature and wind vectors), the Almaty cumulative impact $\delta e^{30}_{24}$ of -1.15 J/kg represents a very substantial 2.9% of the total global cumulative impact from AMDAR ascent observations.(-39.7 J/kg), in spite of the fact that only 0.43% of all global AMDAR ascent observations were from Almaty. In terms of impact per observation, Almaty's value of -8.46 x $10^{-5}$ J/kg represents a beneficial impact 6.7 times that of an average global AMDAR ascent observation! AMDAR temperature observations were particularly important at Almaty, providing almost 90% of the cumulative impact on the forecast error during the 15-month study period. In comparison, the global cumulative impact was 57% from temperature observations and 43% from wind vector observations.

For Almaty, the average impact per radiosonde observation (either temperature, u- or v- wind component, humidity or geopotential) of -3.69 x $10^{-5}$ J/kg is more than 50% larger than the average radiosonde observation impact in the global domain (see Table 1). Even so, this Almaty average radiosonde impact value is considerably less than half the average impact from an Almaty AMDAR ascent observation. To further put in perspective the large beneficial impact of the Almaty AMDAR ascent observations, consider that the cumulative radiosonde impact for Almaty (-1.37 J/kg) is not that much larger than the cumulative impact from the AMDAR observations in spite of the fact that there were considerably more Almaty radiosonde profiles than AMDAR ascent profiles (323 to 189) and a corresponding much greater number of observations (37053 to 13634).

Table 1. Observation impacts $\delta e^{30}_{24}$ (J/kg) (cumulative, per observation, per profile) and related data counts for Almaty, Kazakhstan, and global (worldwide) AMDAR ascent and radiosonde observations assimilated into NAVDAS at 00 UTC during the study period May 2006 – July 2007.

| | AMDAR | | RAOBS | |
|---|---|---|---|---|
| | Almaty | Global | Almaty | Global |
| Cumulative $\delta e^{30}_{24}$ (J/kg) | -1.154 | -39.701 | -1.366 | -743.173 |
| No. Observations | 13634 | 3160810 | 37053 | 31679400 |
| No. Profiles | 189 | --- | 323 | --- |
| No. Days | --- | 338 | --- | 338 |
| Avg. Obs. / Profile | 72.1 | (90) | 114.7 | (150) |
| Avg. Obs. / Day | --- | 9352 | --- | 93726 |
| $\delta e^{30}_{24}$ / Obs. ($10^{-5}$ J/kg) | -8.46 | -1.26 | -3.69 | -2.35 |
| $\delta e^{30}_{24}$ / Prof. ($10^{-3}$ J/kg) | -6.10 | -1.13 | -4.23 | -3.53 |

Monthly average impact per observation values for Almaty and global AMDAR ascent and radiosonde observations are shown in Figure 1. The large observed month-to-month variability for the Almaty data in some part relates to the large monthly swings in data availability. Specifically, the number of Almaty AMDAR ascent profiles varies from a low of 7 in February 2007 to a high of 19 in September 2006 while the number of Almaty 00 UTC radiosonde profiles varies from 14 in November 2006 to a complete 30 in June 2006. For the Almaty AMDAR ascent data, monthly average impact values vary more widely during summer than winter. Of the 15 monthly averages, the 5 least beneficial (i.e., smaller negative number) occur during the warm season May through September, but also 3 of the 6 most beneficial. All impact values during the cold season (November through March) are near or more beneficial than the 15 month average impact of $-8.46 \times 10^{-5}$ J/kg . For Almaty radiosonde monthly average impacts, six of the seven most beneficial occur during the warm season, but also the two least beneficial. In only two of the 15 months (June and September 2006) are average impacts from the Almaty radiosonde observations more beneficial than those from the Almaty AMDAR ascent observations. Finally, when compared to monthly global average impact per observation values, in only one month (July 2007) is the Almaty AMDAR ascent impact less beneficial (and marginally so) than the corresponding monthly global radiosonde average impact. Also note that it is only during this particular month that the Almaty AMDAR ascent average impact per observation is within $1 \times 10^{-5}$ J/kg of the global AMDAR ascent average impact value.

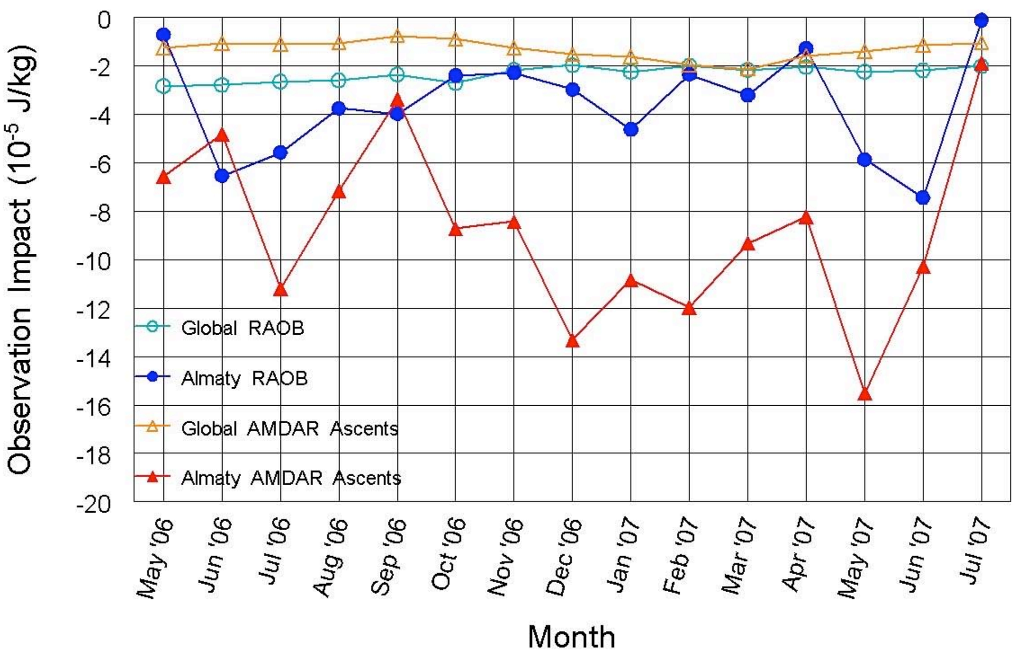


Figure 1. Monthly average impact per observation values for Almaty and global AMDAR ascent and radiosonde observations for the period May 2006 – July 2007.

In addition to quantifying the impact of individual observations on selected forecasts, observation impact may also be quantified in terms of complete radiosonde or AMDAR ascent profiles. As given in Table 1, the average number of observations per AMDAR ascent profile at Almaty over the 15-month study period was about 72, which yields an average impact per profile of -6.10 x $10^{-3}$ J/kg. For the average Almaty radiosonde profile with about 115 observations, the overall average impact per profile is -4.23 x $10^{-3}$ J/kg. These results indicate a somewhat less beneficial impact for an average Almaty radiosonde profile compared to an average Almaty AMDAR ascent profile. In order to compute average impacts per profile in the global domain, estimates of 90 and 150 observations per AMDAR ascent and radiosonde profiles, respectively, were chosen. This first estimate agrees with a reported mean value of 30 observation levels (x 3 observations per level) for an AMDAR ascent profile (Anonymous, 2001), while the second estimate yields a very realistic average number of 625 radiosondes per a typical 00 UTC NAVDAS analysis cycle. Based on these estimates, the global average impact for an AMDAR ascent profile is -1.13 x $10^{-3}$ J/kg and, for a radiosonde profile, -3.53 x $10^{-3}$ J/kg. Comparison of these values with those for Almaty indicates that the average impact of an AMDAR ascent profile at Almaty is 5.4 times more beneficial than that of the global average AMDAR ascent profile, and is considerably greater than the global impact for radiosonde profiles in spite of the AMDAR ascent profiles being composed of about half as many individual observations.

Figure 2 depicts monthly average impacts per profile corresponding to Almaty and global AMDAR ascent and radiosonde profiles. Given the disparity in the number of individual observations which comprise an average AMDAR profile and a radiosonde sounding, there are subtle differences (when compared to Figure 1 data series) in how the Almaty monthly AMDAR ascent profile impact averages rate with those derived from radiosonde profiles. For example, there are three months (June and September 2006, June 2007) during the 15-month study period in which Almaty radiosonde profile impacts prove more beneficial than those due to Almaty AMDAR ascent profiles (two in Figure 1). Also, there are three months (June and September 2006, July 2007) where the average impact for an Almaty AMDAR ascent profile is less than the global average impact for radiosonde profiles (one in Figure 1). Although the presentation of Almaty's AMDAR ascent data in terms of profiles instead of individual observations tends to diminish (or, in a few cases, reverse) its advantage in error reduction over radiosonde data, the fact remains that in the large majority of the months analyzed (12 of 15) Almaty AMDAR ascent profiles have a greater beneficial impact than either Almaty or global average radiosondes in the reduction of forecast error in the global domain.

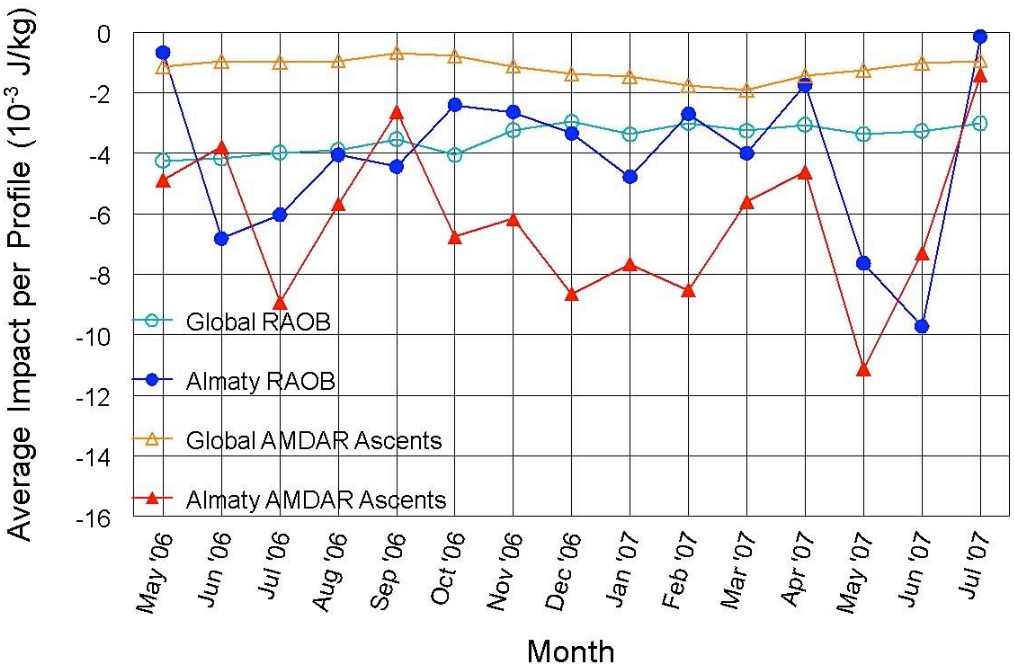


Figure 2. Monthly average observation impact per profile for Almaty and global AMDAR ascent and radiosonde profiles for the period May 2006 – July 2007.

As previously mentioned, in any individual forecast, there are many observations which do not provide a beneficial impact upon forecast error reduction. By summing over all available observation impacts comprising any particular radiosonde or AMDAR profile, a total impact value is obtained. During the 15-month study period, 148 of the 189 Almaty AMDAR ascent profiles, or 78.3%, proved beneficial (i.e. $\delta e^{30}_{24} < 0$). This result is noticeably better than that for the Almaty radiosonde soundings, where 221 of the 323, or 68.4%, had a beneficial impact on forecast error reduction. Figure 3 shows the percentage of beneficial Almaty AMDAR ascent and radiosonde profiles for each month from May 2006 to July 2007. For the AMDAR data, nine months have 80% or more beneficial profiles and only two months with

60% or less. On the other hand, there are only three months with 80% or more beneficial radiosonde data but six months with percent beneficial values less than 61%. In terms of seasonal variability, little is observed with the Almaty radiosonde data. For the Almaty AMDAR ascent profiles, five of every six (83.6%) proved beneficial during the November through March cold season, somewhat larger than the 76.4% beneficial for the May through September warm season.

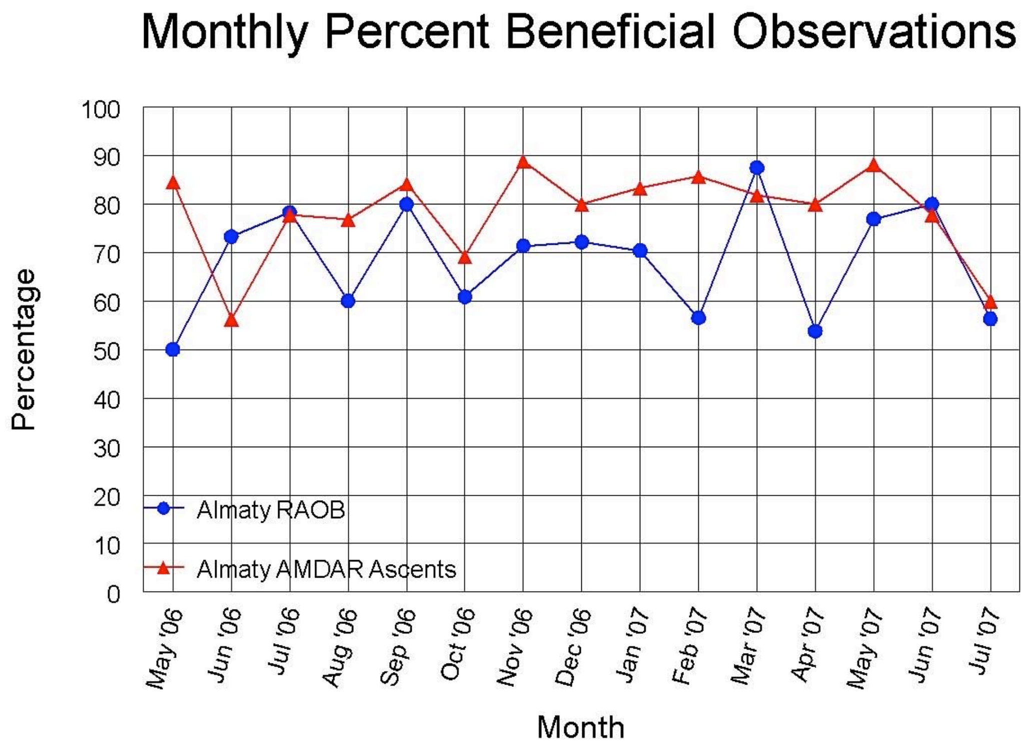


Figure 3. The percentage of beneficial ($\delta e^{30}_{24} < 0$) Almaty AMDAR ascent and radiosonde profiles for each month from May 2006 to July 2007.

## 4. Summary and Discussion

In this study, we have investigated the impact of observations assimilated at 00 UTC from May 2006 through July 2007 over the global domain, targeting for extensive analysis all available AMDAR ascent aircraft reports and routine radiosonde reports at Almaty, Kazakhstan. The "observation impact" is quantified as the difference of forecast error $e_{24} - e_{30}$, where $e_{24}$ is the 24-hr forecast error from initial conditions at 00 UTC and $e_{30}$ is the 30-hr forecast error from initial conditions (i.e., model background) 6-hr prior at 18 UTC. An estimate of this forecast error difference is calculated as a scalar quantity $\delta e^{30}_{24}$ using innovations (observation minus background values) and adjoint-derived sensitivity gradients. This approach provides unique insight into observation impact as it can define impact for each individual observation in a selected forecast. This allows individual observation impacts to be easily quantified as a "cumulative" impact based on all available observations for a particular observation type, or an "impact per profile" for a complete radiosonde or AMDAR aircraft profile.

Except for routine radiosondes and an occasional (not even daily) AMDAR ascent, Almaty and the surrounding area out several hundred kilometers is devoid of in-situ upper-air meteorological observations assimilated into numerical forecast models. As unique observations in a highly variable meteorological setting, these Almaty observations were found to have large beneficial impacts (i.e. $\delta e^{30}_{24} < 0$) when compared to average global AMDAR ascent and radiosonde observation impacts. For example, in terms of "impact per observation," the 15-month average impact value of an Almaty AMDAR ascent observation is 6.7 times more beneficial than that of a global average AMDAR ascent observation, while the average impact for an individual Almaty radiosonde observation is more than 50% more beneficial than the average radiosonde impact in the global domain. Keep in mind that these statistics were generally derived from co-located (both in time and space) AMDAR and radiosonde observations which both compete for forecast impact when used jointly. Thus, for any particular forecast, the impact from either one of these observation types by itself would likely increase significantly. A direct comparison of Almaty AMDAR ascent and radiosonde observations quantified in terms of full profiles indicates a 44% greater beneficial impact for the average Almaty ascent profile in spite of the fact that the average Almaty radiosonde profile was composed of 60% more individual observations than the average AMDAR profile. Overall, almost 4 of every 5 Almaty AMDAR ascent profiles provided a beneficial impact upon the reduction of forecast error, considerably better than the two out of three for Almaty radiosondes. Taken collectively, study results indicate a decisive advantage (i.e. a greater beneficial impact) of Almaty AMDAR ascent observations over Almaty radiosonde observations in the reduction of forecast error in the global domain.

The large beneficial impact on the reduction of short-range forecast error from AMDAR aircraft reports in a data-austere region of high meteorological variability is a very significant result from this study, a result which offers great promise for the beneficial utilization of weather data from unmanned aircraft systems deployed in similar environments. AMDAR flight profiles (such as those from Almaty) typically consist of 30 or so observation levels from the surface to cruising level around 30,000 ft, depending on reporting configuration. Currently, the long-endurance medium-altitude Predator flown by the United States Air Force and others is the most suitable UAS platform available for AMDAR-like surface to mid troposphere atmospheric profiling. As such, the immediate emphasis of the UAS work at NRL is the acquisition of both test and in-theater Predator data and the concurrent examination of how such data impacts the accuracy of short-range forecasts in data-sparse areas. It is anticipated that Predator data will become (in the not too-distant future) the first UAS data accepted for operational use within the Navy's global weather forecast model. At some future time, the impact of weather data from the high-altitude, long-endurance Global Hawk UAS and smaller unmanned aeronautical vehicles of more limited flight characteristics (e.g., Silver Fox) will also be examined. To best exploit model forecast capabilities, plentiful boundary layer data from smaller UAS could be studied within the framework of the Navy's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®).

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